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Supersonically sprayed, triangular copper lines for pool boiling enhancement

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ABSTRACT

Pool boiling is a mechanism by which heat is removed through nucleation of bubbles at the heated surface. Because of the ever-increasing demand for miniaturization of more powerful electronic devices, heat flux requirements grow. Herein, we introduce a rapid, scalable supersonic spray-coating technique that produces micro-scale lines with triangular cross sections. The surface of each triangular line is textured and provides numerous nucleation sites. Pathways of escaping bubbles experience minimal interference because of the triangular shape of the lines. These rising bubbles remove heat efficiently and facilitate rapid cooling. Both critical heat flux and the effective heat transfer coefficient increased significantly under the optimal coating condition, which is identified. The effect of the number of the patterned lines was studied. The coolant contact angle against the lined surface was investigated to quantify wettability and capillary effects. Bubble formation was visualized with a CCD camera and the triangular-shaped lines were characterized by scanning electron microscopy and an optical profiler.

1. Introduction

Over the last decade, the number of internet mobile devices such as smart phones, and tablet PCs has increased exponentially. Nano-scale integrated circuit chips and high-capacity compact batteries have made it possible for these devices not only to provide entertainment, information, and location-based services for personal use, but also to store and manipulate large data sets. However, both of these features are hindered by necessarily increasing heat fluxes and it is expected that classical cooling solutions will not be able to satisfy future thermal demands [1,2]. Enhanced and manufacturing-friendly cooling technologies are subject to the limitations imposed by small overall volumes, light-weight design, and effective cooling performance.

Micro-scale, phase-change, heat-transfer systems such as micro heat pipes and vapor chambers, which are easy to control with no external pumping requirements, are viewed as two of the best potential solutions to thermal-management problems [3–9]. These systems use capillary forces from grooves machined into a wick-like surface. The working fluid evaporates at hot spots and is condensed back to liquid in a cooler region. The pathways of the phase changing liquid are provided by grooved structures that increase capillary forces.

At increased heat fluxes, excessive bubble growth may occur locally, preventing efficient cooling by evaporation. In addition, local dry-spot formation can obstruct pathways of circulating liquid supply during bubble formation. Grooved surfaces have been used to counter these problems through local curvature that increases capillary forces to draw in liquid more efficiently.

The grooves can be constructed by chemical etching, vapor deposition, or skiving during metallic manufacturing, which involves multiple manufacturing steps and therefore inhibit cost competitiveness.

For this reason, we introduce a new technique for constructing grooves in our case (lines) by supersonic spraying, which is rapid, scalable, and commercially viable. Metal particles are entrained into a supersonic stream by expanding pressurized air at high temperatures [10]. By converting the thermal and pressure energy into kinetic energy, a supersonic stream is generated. The accelerated metal particles adhere onto the substrate after passing through a patterned mask. Ultimately, lines with a triangular cross-sectional shape are generated [11].

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Excessive nano-texturing can interfere with the pathways of rising bubbles. A thick nanotextured layer can trap nucleated bubbles leading to increased thermal resistance and hindered pool boiling performance. Our triangular shape facilitates rapid detachment of nucleating bubbles with minimal interference against the rising bubbles (imagine how nucleated bubbles would be trapped if the shape was an upside-down triangle). Bubble coalescence is minimized because of their rapid detachment from the grooves. Therefore, issues of dry out and pathway obstruction are minimized. Ample supply of liquid and continuous wetting are facilitated. These nano-porous lines also result in numerous bubble nucleation sites. The triangular-shaped lines stimulate bubble generation through increased capillary forces allowing for uniform wetting along the line while increasing the area for bubble nucleation.

We have previously shown how nano-scale structures textured on flat surfaces have significant potential for application to miniature electronics cooling devices because wettability, critical heat flux (CHF), and effective heat transfer coefficients (h_{eff}) are notably improved [12,13]. Herein, we expect that increasing the number of lines will increase the CHF and h_{eff} through more nucleation sites and by increasing the surface area. However, too many closely spaced lines can lead to bubble coalescence and film boiling, which would decrease heat transfer.

2. Experimental setup

2.1. Materials

Copper powder (LeesChem Co., Korea) with an average size of 1 μm was used to coat a copper substrate [11]. HFE-7100 (NovecTM Engineering Fluid, 3 M), which is non-ozone-depleting fluid with low toxicity, was used as the coolant in this study. This coolant has a high latent heat of vaporization allowing for enhanced nucleate boiling and CHF. Table 1 lists the physical properties of HFE-7100 [14].

2.2. Supersonic spray coating

The supersonic cold spray setup consisting of a compressor, powder feeder (Praxair 1264i, USA), nozzle, and an *x-y* stage (Fig. 1) was used to pattern the substrate with multiple triangular-cross-section copper lines. The compressor operated at $P_0 = 6$ bar and the gas temperature was $T_0 = 320°\mathrm{C}$ to add thermal energy to the accelerating air, which converted to kinetic energy yielding a supersonic air stream. The nozzle-to-substrate distance was 55 mm and the size of the masks used to produce the patterned lines was $50 \times 50\ \mathrm{mm}^2$. The steel masks have variable-spaced rectangular slits to pattern the lines. The powder feeder supplied Cu particles at 25 L/min and the particles were coated onto the substrate along the length of mask as the nozzle travels at 35 mm/s for a total of two passes. The number of Cu lines (N_{line}) was developed as shown in Fig. 2a.

2.3. Pool boiling experimental setup

Pool boiling tests were carried out using the experimental setup shown in Fig. 3. Part 1 (Fig. 3a) of the test section consists of a test sample, three thermocouples, an aluminum rod for transferring heat from heaters to the sample, four heaters, and a Teflon case. Part 2 (Fig. 3b) of the boiling experiment includes a condenser, three preheaters, a thermocouple, a test chamber, and a Teflon cap.

Four cylindrical cartridge heaters in an aluminum rod ($k_{\mathrm{Al}} = 210\ \mathrm{W\,m^{-1}\,K^{-1}}$) were connected to the power supply (Slidac, 1 KVA, Dae Kwang Electric Co) and three K-type thermocouples (Omega Inc. with accuracies of ±0.3°C, thickness = 1 mm) were placed along the rod at regular intervals of 8 mm to measure three different temperature (T_1, T_2, and T_3). By encapsulating the rod in a Teflon case and cap ($k = 0.25\ \mathrm{W\,m^{-1}\,K^{-1}}$), heat losses were minimized. The sample was fixed using a thermal grease (DOW CORNING, TC-5026, $k_g = 2.89\ \mathrm{W\,m^{-1}\,K^{-1}}$) to reduce contact thermal resistance between the sample and the aluminum rod.

Table 1
Physical properties of the HFE-7100 Engineering fluid.

Physical properties	HFE-7100 (0.1 MPa)
Boiling point (°C)	61
Density of liquid ($\mathrm{kg\,m^{-3}}$)	1370.2
Density of vapor ($\mathrm{kg\,m^{-3}}$)	987
Viscosity of liquid ($\mathrm{kg\,m^{-1}\,s^{-1}}$)	3.70×10^{-4}
Surface tension of liquid-vapor interface ($\mathrm{N\,m^{-1}}$)	1.019×10^{-2}
Specific heat of liquid ($\mathrm{J\,kg^{-1}\,K^{-1}}$)	1255
Enthalpy of vaporization ($\mathrm{J\,kg^{-1}}$)	111.6

The test chamber was held between top and bottom aluminum plates and three preheaters were submerged in the coolant. To maintain the saturated temperature of the coolant, the preheaters were supplied 30 V by the power supply (Slidac, 0.5 KVA, Dae Kwang Electric Co). The condensing unit, a spiral tube circulating cooling water at 5°C from the chiller (AP15R-30-V11B, VWR Ad), was connected to the top aluminum plate to maintain coolant levels.

Prior to the experiments, the temperatures of the coolant and sample were stabilized by applying 60 V to the four cartridge heaters for 30 min and pool boiling tests started when the coolant temperature varied no more than ±0.1°C. Voltage was stepped at 5 V every 10 min so that the temperatures of three thermocouples reached steady state. Voltage steps continued until pool boiling was achieved and the substrates reached CHF, which was identified as the last steady-state heat value before temperatures rose sharply.

2.4. Characterization

Cross-sectional and plan views of a Cu line were measured by a field-emission scanning electron microscope (FE-SEM, S-5000, Hitachi) at 15 kV. Roughness and 3D images were characterized by an optical profiler (Veeco, NT-1100). Capillary phenomena were measured by dipping the sample into a coolant and taking snapshots with a high-speed camera (Phantom 9.1, Vision research Inc.). Coolant contact angles were analyzed using an image-capture and measurement solution (I'MEASER 3.0, ING. PLUS).

3. Results and discussion

3.1. Triangular copper lines

Fig. 2b shows the morphology of the line. As in the previous study [11], Cu particles were sprayed uniformly through the nozzle, but preferentially deposited in the center because of recirculation zones forming at each edge of the mask. As a result, Cu particles were deposited in a triangular shape as shown in Fig. 2b. In addition, the height of the triangle increased as the number of coating passes increased [11]. For this study, the number of spray passes was fixed at 2 and the height (h) and width (w) of the triangular Cu line were 128 and 348 μm, respectively, and thus their aspect ratio was $\gamma = h/w = 0.37$. In conjunction with the SEM images, 3D images from an optical profiler were acquired as shown in Fig. 2c, which shows the patterned lines for various spacing (λ). The h of these triangles was constant for all three cases.

At $\Delta T_{\mathrm{sat}} = 13°\mathrm{C}$ (Fig. 4a), bubble sizes were fairly uniform across the three cases and there was only a slight difference in the num-